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Final Report

The Ionospheric Plasma Research Experiment: ASUSat 1 & Advanced Spacecraft Technology Applications

submitted to

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Abstract

This final report describes efforts to sustain a unique educational opportunity for undergraduate students to team in the design, fabrication, and launch of small satellite systems. Our program impacts a broad spectrum of interested science and engineering students, providing hands-on experience in low-cost space experimentation. Local industry professionals and Arizona State University faculty have enthusiastically volunteered as technical advisors. Local companies have also been approached to provide other resources such as testing and fabrication facilities.

In October 1993, the students at Arizona State University (ASU) were challenged by Orbital Sciences Corporation (OSC) to develop a 4.5-kg (10-lb) satellite (ASUSat 1) to be launched as a piggyback payload on a Pegasus rocket. The challenge also included the requirements for the satellite to perform meaningful science and to fit in the payload adapter cone section above the avionics (0.02 m^3). Moreover, the students were faced with the cost constraints associated with university satellite projects. This unusual set of constraints resulted in a design and development process which is fundamentally different from that of traditional space projects. The spacecraft capabilities and scientific mission evolved in an extremely rigid environment where cost, size and weight limits were set before the design process even started. In the ASUSat 1 project, severe constraints were determined first, and then a meaningful scientific mission was chosen which fit those constraints. This design philosophy can be applied to future interplanetary spacecraft. In addition, the ASUSat 1 program demonstrates that universities can provide an open-minded source for the innovative nanospacecraft technologies required for the next generation of low-cost planetary missions, as well as an economical testbed to evaluate those technologies. At the same time, the program provides hands-on training for the space scientists and engineers of the future.

Approximately thirty-five students work on the project each semester, most are undergraduates. Course credit is offered in the Mechanical & Aerospace Engineering (MAE) and Computer Science & Engineering Departments, and senior design credit is available through MAE and Electrical Engineering. Once each week the entire group meets. Each sub-system meets separately, and the group leaders meet in a weekly systems meeting. The (usual for industry) design reviews are put on by the students with significant industry participation to ensure the project's success. The weekly report required of each student ensures timely progress toward team and individual goals.

The objectives of the program are to provide "relevance" to the undergraduates' complementary basic-science and engineering-fundamentals classes; hands-on awareness of the product design and manufacturing process; a multi-disciplinary, systems perspective; a basic understanding of the context in which engineering is practiced; communication skills - listening, writing, verbal, graphic; high ethical standards; an ability to think both critically and creatively - independently and cooperatively; flexibility; curiosity and a desire to learn for life; a profound understanding of and commitment to team work; and leadership and management skills. In the process, a broad group of undergraduates are impacted who will now be excited and prepared to pursue research and innovation in industry or graduate school. Further details on our program are available on the World Wide Web at: http://www.eas.asu.edu/~nasasg/. Plus, the ASUSat team was featured as the cover story in *Graduating Engineer* (from Peterson's Magazine Group), Volume 18, Issue 1, September 1996, and was the subject of an article in *PRISM* from the American Society of Engineering Education this coming April. The team was also invited to participate in a Poster Session on Capitol Hill on April 10, 1997, with the purpose of educating the legislators to the importance of undergraduate research.

1. INTRODUCTION

This fianl report describes efforts to sustain a unique educational opportunity for undergraduate students to team in the design, fabrication, and launch of small satellite systems. Section 2 describes our tangible accomplishments to date for this program. Section 3 gives the technical details on the project. Appendix A contains a resume for Dr. Reed, the principal PI.

2. ACCOMPLISHMENTS TO DATE

A) Publications

Archival refereed journal papers

"ASUSat 1: An Example of Low-Cost Nanosatellite Development," J. Rademacher, H.L. Reed, and J. Puig-Suari, *Acta Astronautica*, Volume 39, Number 1-4, Pages 189-196, 1996.

"ASUSat 1: A Low-Cost Amateur Radio Nanosatellite," S. Ferring, J.D. Rademacher, C. McAllister, A. Friedman, H.L. Reed, J. Puig-Suari, *AMSAT Journal*, Volume 20, Number 3, Pages 12-17, 1997.

Refereed national conference proceedings papers

"Preliminary Design of ASUSat 1," J. Rademacher (Student Author), under H. Reed (Faculty Advisor), *AIAA/USU 8th Annual Small Satellite Conference*, Finalist - *2nd Annual AIAA Small Satellite Student Scholarship Competition* (organized by Jayne Schnaars of Rockwell International and Bob Meurer of Orbital Sciences Corporation), August 29 - September 1, 1994.

"A Microparticle Recognition Experiment for Near-Earth Space on Board the Satellite ASUSat 1," C. Hewett (Student Author), under H. Reed (Faculty Advisor), *AIAA/USU 8th Annual Small Satellite Conference*, FIRST PLACE - *2nd Annual AIAA Small Satellite Student Scholarship Competition* (organized by Jayne Schnaars of Rockwell International and Bob Meurer of Orbital Sciences Corporation), August 29 - September 1, 1994.

"The Ionospheric Plasma Research Experiment on Board the Satellite ASUSat 1," C. Hewett, J. Rademacher, H.L. Reed, J. Puig-Suari, *ST-95-W.1.07, 25th IAF Student Conference* at *46th IAF Congress*, Oslo, Norway, October 2-6, 1995.

"Ionospheric Technology: ASUSat1 & Advanced Spacecraft Propulsion Systems", C. Hewett (Student Author), H.L. Reed, J. Puig-Suari (Faculty Advisors), *AIAA/USU 9th Annual Small Satellite Conference*, FIRST PLACE - *3rd Annual AIAA Small Satellite Student Scholarship Competition* (organized by Jayne Schnaars of Rockwell International and Bob Meurer of Orbital Sciences Corporation), September 18-21, 1995.

"Earth Reference Imager Experiment for Satellite Attitude Determination", J. delaTorre, Jr. (Student Author), J. Puig-Suari, H.L. Reed (Faculty Advisors), *AIAA/USU 9th Annual Small Satellite Conference*, FINALIST - *3rd Annual AIAA Small Satellite Student Scholarship Competition* (organized by Jayne Schnaars of Rockwell International and Bob Meurer of Orbital Sciences Corporation), September 18-21, 1995.

"The Ionospheric Plasma Research Experiment: ASUSat 1 & Advanced Spacecraft Technology Applications," C. Hewett, J. Rademacher, H.L. Reed, J. Puig-Suari, *AIAA 34th Aerospace Sciences Meeting and Exhibit, AIAA-96-0719*, January 1996.

"ASUSat 1: An Example of Low-Cost Nanosatellite Development," J. Rademacher, H.L. Reed, J. Puig-Suari, *2nd IAA International Conference on Low-Cost Planetary Missions, IAA-L-0516*, Laurel, Maryland, April 16-19, 1996.

"ASUSat 1: A Low-Cost AMSAT Nanosatellite", S. Ferring, J.D. Rademacher, H.L. Reed, J. Puig-Suari, and other members of the ASUSat 1 Team, *1996 AMSAT Annual Meeting and Space Symposium*, Nov. 8-10, 1996.

Invited Presentations

"Student Projects in Aerospace," H.L. Reed, *Invited Seminar*, American Physical Society/Division of Fluid Dynamics Special Workshop for High-School Physics Teachers, University of California/Irvine, November 20, 1995.

"ASU's Aerospace Research Center," H.L. Reed, *Amelia Earhart Distinguished Lecturer*, Zonta Club International, Tempe, January 25, 1996.

"ASU's Small-Satellite Program: ASUSat 1," J.D. Rademacher, D. Staggers, and H.L. Reed, *Invited Presentation*, OSC Microsat Secondary Payload Carrier (MSPaC) Interim Design Review, Feb. 21, 1996.

"ASUSat 1 and Future Small-Spacecraft Technology," H.L. Reed and J.D. Rademacher, *Invited Talk*, National Engineers' Week, Honeywell Space Systems Group, February 21, 1996.

"ASUSat 1," H.L. Reed and J.D. Rademacher, *Invited Talk*, ASME Local Chapter, April 11, 1996.

"Student Projects in Aerospace," H.L. Reed, Invited Talk, Bachelor of Interdisciplinary Studies "Approaches to Interdisciplinary Studies" Miniconference, ASU, April 12, 1996.

"ASUSat 1 - A Student Designed and Tested Satellite," H.L. Reed, *Invited Talk*, American Association of Physics Teachers, Southern California Section, April 27, 1996.

"ASUSat 1," H.L. Reed and J.D. Rademacher, *Invited Poster Talk*, National NASA Space Grant College and Fellowship Meeting, Williamsburg, Virginia, May 22, 1996.

"ASUSat Lab and Moon Devil," H.L. Reed, *Invited Talk*, Saguaro High School, Scottsdale, September 24, 1996.

" ASUSat 1 - A Student Designed and Built Satellite," H.L. Reed, *Invited Seminar*, American Physical Society/Division of Fluid Dynamics Special Workshop for High-School Physics Teachers, Syracuse, November 25, 1996.

B) Support for the team, in the form of mentoring and assessment, hardware donations, student support, and use of fabrication and testing facilities has been secured as follows.

Orbital Sciences Corporation	Pegasus/Taurus-rocket launch, advising, test facilities
NASA Space Grant Program	student internships and fellowships
National Science Foundation Faculty Awards for Women in Science and Engineering	student funding
AMSAT Organization	advice on spacecraft design, guidance regarding its qualification as Amateur Radio Satellite

Honeywell Space Systems Group	advising in all areas, cash donation
Hughes Missile Systems	advising, electronics troubleshooting, use of facilities, cash donation
Space Quest	communications advising and support
Dycam	on-board cameras
Motorola (Satcom & University Support)	thermal, power, and communications advising IC, crystal, and receiver donations
PhotoComm, Inc.	solar array advising and facilities
Eagle Picher Industries	advising (battery algorithm), batteries
Intel (University Support)	processor, literature, In-Circuit Emulator (ICE), test equipment donations
Maxon	donation of flight transmitter boards
Universal Propulsion Company, Inc.	advising, explosive bolt cutter donation
ICI Fiberite Composites	advising, composite material
DynAir Tech of Arizona (now SabreTech)	advising, autoclave usage, composite material, facilities for manufacturing parts
National Technical Systems	environmental testing
SpectrumAstro	communications testing
Trimble Navigation	GPS board and antenna, advising
Bell Atlantic Cable	ground station antenna cabling
Lee Spring Company	prototype deployment springs
Astro Aerospace	advising, boom material donation
BekTek	software advising
Jet Propulsion Laboratory	non-flight transmitter donation
Rockwell	non-flight solar-cell donation
Sinclabs, Inc.	non-flight test antenna donation
Applied Solar Energy Corporation	discounted hardware, advising
Gordon Minns and Associates	on-board cameras
Communication Specialist	decoders
Simula, Inc.	structural-analysis advising
KinetX	advising on software and ground support
Equipment Reliability Group	advising on testing equipment
Arizona State University	hardware funding
ASU/Architecture & Environmental Design Shop	machining facilities
ASU/Center for Solid State Electronics Research	clean-room advising, use of equipment and lab space
ASU/Telecommunications Research Center	use of anechoic chamber
ASU/Electrical Engineering Department	loan of testing equipment

C) Mr. Charles Hewett (Chief Scientist, NASA Space Grant Intern, and Physics & Astronomy Undergraduate) received the top award in the student competition at both the 8th and 9h Annual AIAA/USU Small Satellite Conference in Logan, Utah in 1994 and 1995. The ASUSat 1 team received the 1995 Bronze (ASU) President's Medal for Team Excellence.

D) The ASUSat team was featured as the cover story in *Graduating Engineer* (from Peterson's Magazine Group), Volume 18, Issue 1, September 1996, and was the subject of an article in *PRISM* from the American Society of Engineering Education this coming April. The team was also invited to participate in a Poster Session on Capitol Hill on April 10, 1997, with the purpose of educating the legislators to the importance of undergraduate research.

E) ASUSat 1 faculty advisor Helen Reed received:

Teaching Excellence Award in the Undergraduate Category, CEAS, ASU, 1993-94
Outstanding Graduate Faculty Mentor, Graduate College, ASU, 1994-95
Distinguished Mentor of Women Award, Faculty Women's Association, ASU, April 17, 1996

Member of ASU Team selected as Finalist for Boeing Outstanding Educator Award, Spring 1997
Fellow, American Society of Mechanical Engineers, July 1997

and was appointed the new Associate Director of the ASU NASA Space Grant Program, effective December 1, 1994 through the next five years.

F) Team members (undergraduate and high school students, too!) serve as ambassadors and role models, promoting interest in mathematics and science, undergraduate research, and ASU. The team is quite enthusiastic about taking their "show on the road" to local K-12 schools.

G) Student benefits:

"ASUSat 1 represents a truly innovative and rewarding research opportunity not available elsewhere to the undergraduate. Students from Geology, Physics, Mathematics, Computer Science, Aerospace, Mechanical and Civil Engineering are but a few served by the scope of this project. But it is here, within the unique perspective that each student brings to this diverse group, that the learning experience truly begins. The exchange of ideas brought forth from outside their usual scope of influence, provides a degree of insight that is not available through any other medium. Dr. Reed, and the Student Satellite Program affiliates, are to be commended for their efforts and contributions to improving undergraduate education."

Charles Hewett, Sophomore -- Physics & Astronomy, University Honors College

"Working on ASUSAT1 has been the most career preparing, motivating, challenging, and exciting collegiate activity I have experienced thus far in my undergraduate college studies. This project has not only linked me up with cutting edge aerospace technology, but has also allowed me to innovate within its world. Real-time engineering is an opportunity very seldom handed down to undergraduate students, it is for this reason that I am very grateful to be working on the design and construction of ASUSAT1. Not only does this project provide me with a valuable educational experience, but it also gives me the opportunity to pave a road for other Hispanics to follow, as I strive to encourage them to study the very many engineering and science fields."

Christopher M. Martinez, Sophomore -- Aerospace Engineering

"The chance to do undergraduate research has provided me with invaluable experiences and hands on knowledge that cannot be learned in the classroom. Right away, I found myself learning material that I had not even studied yet, and in many instances, will never get to study either. The best part is, though, the networking with other disciplines, other students and faculty, and even several professionals. Our research requires that we not only be familiar with our own specialties, but that we have a broad knowledge of the other areas as well. This undergraduate research experience is one which has enhanced my knowledge and understanding of classroom material, and has encouraged me to pursue more research in graduate school."

Jose' delaTorre, Jr., Sophomore -- Mathematics

"Being a part of this project has been invaluable because of the exposure that it gives us as students to those things which are normally not encountered as part of an undergraduate education. I have seen things that were taught us in the classroom applied to an actual physical entity, and not one that is going to stay in the lab. This is perhaps the most exciting part of the project. I have also been able to interact with industry contacts on a regular basis. I get the opportunity to interact with other students from all different backgrounds. From high school to Graduate students, from computer science to physics to geology. Many of the non technical skills, the teaming and communications which are so poorly taught in the classroom, are taught naturally in this project environment. I can honestly say that as a graduating senior, I feel much more prepared to face the future having worked on this project."

Media Petraglia, Senior -- Mechanical Engineering

"Being part of the ASUSat 1 project at ASU is the best experience I have ever had since coming to the US as a student. Even though I just started as a freshman I was incorporated into the team quickly and was able to contribute in my own way. This greatly enhanced my positive attitude towards college and also showed me many ways to apply what I had just learned in class. Things, such as elementary physics or calculus suddenly made sense, they became my tools - and when I went to my regular classes I was always hoping to learn a new tool to use for my project. In my opinion there is no better way to get used to a team-work atmosphere in which communicative skills are equally necessary as academic abilities - a real world situation. Such a project is a good, if not the best, way to experience "the real world", to acquire leadership abilities and responsibilities, to apply and gain knowledge and last but not least simply enjoy science."

Christian Lenz (from Germany), Freshman - Aerospace Engineering

"This past January I had just finished an internship and I was returning to school to finish my studies in Mechanical Engineering. At that time I was completely unmotivated for demands that would be placed upon me by the engineering curriculum. However, a friend of mine suggested that I take Satellite Design with him. He gave me a small description of the project, saying that the objective was to design a 10 lb. satellite that would collect useful science. At that time, however, I did not realize what kind of an impact the project would have on my education; I figured that I would do my part of the project, earn my academic credits, and continue on towards graduation. As the semester progressed, however, I found myself becoming more and more involved in the design project. In fact it completely changed my perspective on school as a whole. Finally, I had a sense of how I could apply all of this technical information in a real life situation. As a result, I began to take a renewed interest in all of my classes. With this new found drive, I finished the semester with the best academic performance of my entire life. As of now I have been with the project for nearly a year and I am still benefiting from the daily "real world" experience of ASUSat1. If I were in a position to change the academic curriculum for all engineering students across the country, I would set up a series of hands on project similar to ASUSat1. I feel it is the only way to prepare students for life in the "real world"."

Dave (Magner) Ward, Senior -- Mechanical Engineering

3. Student Project: Progress to Date

3.1 Introduction

University satellites provide a unique opportunity to combine the educational and research missions of a university in a single program. The students are presented with a multidisciplinary work environment, where team effort is a must. This experience, while it represents the real working environment of most engineers today, is still unusual in a university setting. On the other hand, the limited resources and rigid constraints placed on these kinds of spacecraft require the development of innovative technical solutions. These new solutions range from the design of new low-cost components to the development of manufacturing techniques that can be easily performed by students with little manufacturing experience.

In recent years, the space community has been faced with new constraints, lower budgets, shorter design times, etc. (the faster, better, cheaper philosophy). In this new environment, the kind of thinking found in university satellite programs may provide some of the solutions which are required for the success of space exploration in the future. This paper describes the ASUSat 1 project. This is only one of the many university satellite programs currently under development. It is the authors' opinion that such projects can make valuable contributions to the aerospace field, not only by training scientists and engineers, but also as a tool for the development and testing of new technologies.

3.2 Program Overview

The original challenge made to ASU students by Orbital Sciences Corporation (OSC) co-founder Scott Webster in October 1993 was to design and build a 4.5-kg satellite to perform meaningful science in space. The satellite would be placed in the payload adapter cone section above the avionics of the Pegasus rocket, with dynamic envelope constraints of 31 cm in diameter and 26 cm in height. Given these mass and size constraints along with the limited resources of a university satellite project, some design limitations were placed on the spacecraft:

(1) In order to reduce mass and complexity, which increases failure risks, the number of deployable systems was to be kept to a minimum. In particular, deployable solar arrays were not considered as an option, and power was to be provided exclusively by body-mounted arrays.

(2) Given the reduced power output from the small arrays along with the severe mass and cost constraints, active control systems were eliminated from the design.

(3) Given the strict mass constraint, innovative approaches had to be considered for structural design, including extensive use of composites.

(4) Due to the cost and mass of commercially available attitude-determination systems, it was decided that a low-cost student-designed attitude-determination system would be developed. Such a system could not guarantee great accuracy, hence the satellite should be able to perform its mission with limited attitude knowledge.

Given these constraints, the mission and final design of ASUSat 1 were dependent on the launch orbit provided by OSC. Launch availability has changed three times since the program began thus producing four missions and satellite designs.

The initial design was based on a 450-km-altitude, 6am-6pm, sun-synchronous orbit. In this orbit, the scientific mission was to measure the flux, mass, velocity, and temperature of microparticles in low Earth orbit. The scientific instrument developed by the students, the Micro Particle Recognition Experiment (MRE), incorporated the use of a thin, piezo- and pyro-electric

polyvinylidine fluoride (PVDF) film to characterize interplanetary dust and microparticles[1]. The spacecraft design included a gravity-gradient boom for stability. After the preliminary design of this spacecraft was completed, the available orbit changed.

The new launch opportunity was a 325-km-altitude, 6am-6 pm, sun-synchronous orbit. Unfortunately, the PVDF film in the MRE would be quickly eroded by atomic oxygen at this lower altitude. Hence, a new experiment had to be developed. At this stage of the design, few components were completed and a significant redesign was still possible without large increases in cost. The new mission involved the study of the ionospheric plasma environment found in the highest layers of the atmosphere. The Ionospheric Plasma Research Experiment (IPRE)[2] involved the measurement of plasma flows and the effectiveness of Hall accelerators using the atmospheric plasma. In addition, the design incorporated two CMOS (complementary metal-oxide semiconductor) cameras for earth imaging which would also be used as a secondary means to determine spacecraft attitude[3]. The large aerodynamic forces associated with the atmospheric density at the lower altitude prevented the use of the gravity-gradient boom for stabilization, and an innovative stabilization system was developed to maintain proper orientation of the scientific instruments.

This design had to be abandoned when the launch was moved again, this time to a 550km-altitude, 10:30am-10:30pm, sun-synchronous orbit. Ion densities at this altitude are not sufficient to run the IPRE effectively, and the science mission required redesign once more. At this point, the development of the spacecraft was in a very advanced stage and some of the most important components, such as the composite structure, were already constructed. The decision was made to reduce the scientific scope of the mission to Earth imaging and the demonstration of our low-cost satellite technologies, along with the AMSAT voice repeater. This new scientific scope required replacing the previous cameras with two higher resolution units. This design allowed for a vehicle able to perform in a variety of orbits, thus reducing risk if further changes in the launch opportunity developed.

In Fall 1996, the launch opportunity was changed again. The new plan is for ASUSat 1 to be the tertiary payload on a Taurus rocket. With the modular philosophy implemented in the previous design, ASUSat 1 did not have to change much for the new orbit of 778 X 790 km and inclination of 108 degrees. This latest version of the satellite is the one described in detail in this final report.

3.3 ASUSat 1

The mission of ASUSat 1 is one of technology demonstration and earth imagery, along with AMSAT operations. ASUSat 1 has several innovative, low-cost aspects incorporated into its design. This includes the two terrestrial cameras; the monocoque composite structure; the terrestrial GPS (global positioning system) unit; and the student-developed array of attitude-determination sensors, small gravity-gradient boom-deployment mechanism, gravity-anchored passive spherical fluid damper, and electronics boards.

3.3.1 Structure

In order to meet the low-weight constraints on ASUSat 1, the satellite body is constructed of a low-cost, light-weight carbon fiber in a 954-2A cyanate resin manufactured by ICI Fiberite Composites. The composite is a 12-layer lay-up with 0°, 45°, -45°, and 90° plies. The total structural weight is 1100 grams, which includes epoxies, fasteners and aluminum brackets. The main bus structure is a 14-sided cylinder inscribed within a 31-cm-diameter circle, with a height of 24 cm, and wall thickness of 0.8 mm. This extensive use of composite materials presents some uncertainties in the analysis of the in-orbit thermal behavior of the satellite, since experience with

composites in spacecraft applications is limited. In order to address these uncertainties, ASUSat 1 incorporates a number of student-designed thermal sensors which will provide an accurate thermal picture of the spacecraft. This data will be valuable to validate currently available thermal computer models.

The structure consists of several sub-assemblies designed for ease of fabrication. This is an important issue since students, with limited manufacturing experience, will construct the satellite. The sub-assemblies are as follows: the 14-sided main body; the removable top bulkhead, mounted flush with the top end of the satellite; the permanent science bulkhead, which is recessed 4 cm into the lower side of the spacecraft; two removable interior instrument and board mounting panels placed between the two bulkheads; the fixed deployment guide rod tube running through the center of the satellite; and brackets at various angles to mount all sections together. The various components are assembled using a combination of space-grade epoxies, aluminum standoffs and stainless steel bolts. The satellite is attached to a student-designed deployment mechanism, which can be easily mounted to an interface plate in most launch vehicles (Figure 1 : Deployment interface).

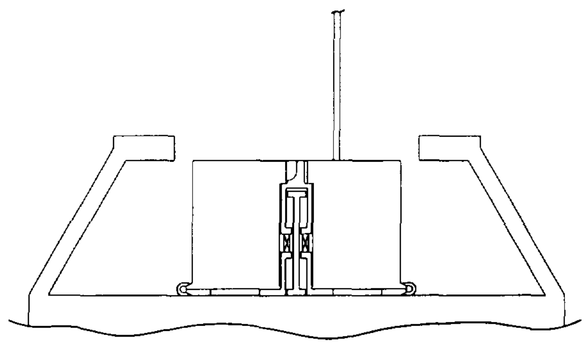

Figure 1 : Deployment interface

3.3.2 Deployment

The deployment mechanism was developed to safely eject ASUSat 1 from the payload adapter cone section above the avionics of the Pegasus rocket. This system was also designed to provide reliable deployment and a simple interface when used in other launch vehicles. This flexibility is important for future ASUSat missions given the limited resources of a university program. The deployment mechanism did not have to be modified with the change of launch to the Taurus mission.

The satellite-deployer system consists of the following components: an extending guide mechanism running through the center guide tube in the satellite; a separation spring located in the guiding device; a clamp band to secure the satellite during launch; a bolt cutter; and a base plate to mount the system into the launch vehicle.

The deployment sequence begins with a pyrotechnic signal to the boom deployer. This guarantees that the satellite is deployed in a stable configuration. This is particularly important for ASUSat 1, since there is not any active attitude-control system present. After a 15-second delay, a second signal activates the deployment bolt cutter. This releases the clamp band, which is pulled away by retraction springs. The separation spring pushes the satellite out of the payload adapter cone section above the avionics at about 0.5 m/s, and the antennas automatically deploy after the spacecraft separates from the guide rod (Figure 1 : Deployment interface).

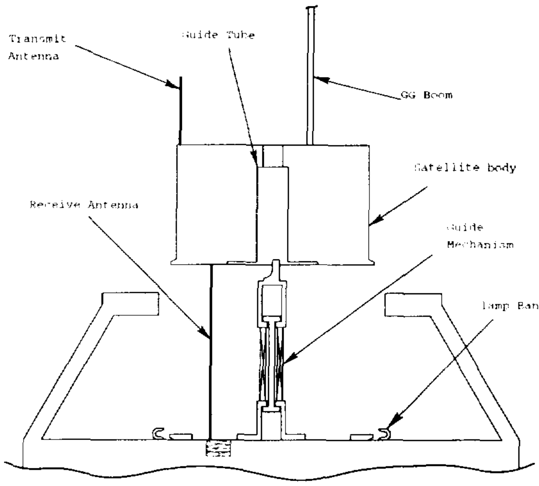

Figure 2 : Deployment

3.3.3 Dynamics & Control

The satellite uses gravity-gradient stabilization with a boom extended from the satellite top. The student-designed boom deployer is based on currently available systems, but has been miniaturized to fit within a 8 x 5 x 5 cm volume. This mechanism deploys a 2-meter beryllium copper element with a 130g copper tip mass.

A passive damper is included in the design to eliminate oscillations on the satellite due to possible deployment misalignments or external disturbances. The damper is a gravity-gradient-anchored system[4]. In this device a gravity-gradient-stable mass is suspended inside a fluid. Given the near-polar orbit of the satellite, this passive damping system is superior to traditional magnetic dampers. In addition, if the mass is designed to be 3-axis stable, the system can provide 3-axis damping. The presence of the passive damper results in a much better imaging platform for the cameras. This gravity-anchored damping mechanism is one of the innovative technologies being tested on ASUSat 1.

A commercial (non-space-rated) GPS unit from Trimble Navigation provides position and velocity information. Modifications to the GPS receiver were performed by the students to improve its resistance to shock and vibration. The unit has been successfully tested to flight qualification levels, and software corrections will be incorporated to remove the COCOM altitude and velocity restrictions.

A low-cost array of student-designed light-sensing diodes is used for attitude determination. A block of four diodes is mounted onto each of the 14 sides of the satellite. Three of the diodes sense visible light from the sun and one senses infrared radiation from Earth. Two more visible-light-sensing diodes are mounted on each bulkhead. All 60 sensors are read periodically to determine the orientation of the satellite. It is estimated that these sensors will provide attitude knowledge with an error of less than 10°. During the mission, Earth images from the cameras will be used to accurately calibrate the sensors and determine a more precise error estimate.

3.3.4 Imaging System

The imaging system on ASUSat 1 consists of two Dycam cameras and boards, one being color and the other a 256 grayscale. The cameras are mounted on the bottom bulkhead and provide overhead pictures of the Earth. Both cameras connect to the commands board by a serial link. One of these cameras incorporates a red and near infrared filter while the other camera has a blue filter. Each 50k

compressed picture can be stored on the camera board in the 1 megabyte of flash memory. The cameras have a 496 X 365 pixel array with a FOV of 18 degrees and a resolution of about 0.5 km per pixel. Image targets are open to the scientific community and all images will be posted and available for public use on the web. Images will also be made available to ham radio operators worldwide.

3.3.5 Electronics

The CPU is designed around the Intel 80C188EC embedded microprocessor. The board has a 2-KB PROM for boot-loader software, a 256-KB EPROM where spacecraft-operations software is stored, and 1 MB of RAM with a two-bit error detection and one-bit correction system. The CPU will initiate power-switch control for the power board, connect to a Zilog Z85230 HDLC controller for digital communication, and interface directly to the GPS board.

Analog measurements from the attitude-determination and thermal sensors are handled by a separate dynamics-interface board. This board is mounted directly on top of the commands boards and is connected by a serial link.

The satellite carries a total of 10 printed-circuit boards, plus 16 attitude-sensor boards. Four of the boards, along with the attitude sensors, are completely student designed. A block diagram of the satellite control boards is shown in Figure 3.

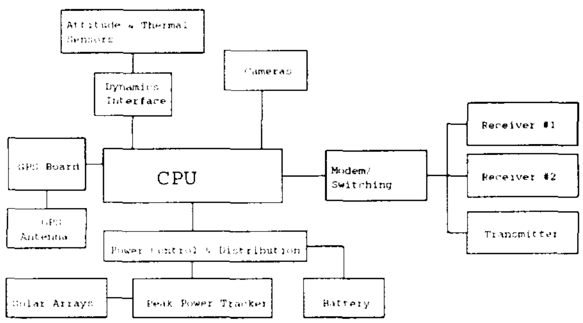

Figure 3 : Control Block Diagram

3.3.6 Power

The power system consists of the solar arrays, two six-packs of Nickel-Cadmium (NiCd) batteries, and associated control electronics.

The solar cells are space-rated Gallium-Arsenide (GaAs) cells with 18.5% efficiency. They are body mounted on all 14 sides and the top bulkhead. Each of the 14 side-panels contains two 15-cell panels. Six additional 15-cell panels are placed on the top bulkhead. Approximately 13 volts are provided from the 34 panels in parallel. This system will provide an average of 8 to 12 watts depending on solar-array temperatures and attitude.

The batteries will provide backup power in high-power-demand situations and during eclipses. The two packs will be used one at a time during the mission. Each pack provides 7.2 volts to DC-DC converters. Battery recharging is controlled by three peak-power trackers. However, they do not provide enough power to run all systems during the 36-minute eclipse associated with the current orbit. The satellite will be placed in a low-power mode during eclipses. In this mode, in order to prevent the loss of software and data stored in RAM, only the CPU is on-line. In addition, critical systems, such as the transmitter and receiver, are kept warm to prevent temperature damage.

The power system is activated by the release of two redundant push-button switches upon deployment of the satellite.

The batteries are the heaviest component on the satellite, while the solar cells are the most expensive.

3.3.7 Communications

The communications system consists of a modem/switching board, partially designed by students, a RM753 transmitter and two receivers. The RM753 is a Maxon unit modified to work in the 420 to 440 MHz range. The receivers are Motorola P-50 Radius Radio transceivers modified by the students with support from Space Quest for use in the space environment.

ASUSat 1 is an amateur-class satellite operating in the amateur-radio-band frequencies. The transmission frequency is in the 70-cm band, while the two receivers operate at separate frequencies within the 2-meter band. One receiver is used for digital mode. The second receiver handles AMSAT voice communications and acts as a backup for the digital system. The modem operates at 9600 baud and interfaces with the CPU using HDLC-frame protocol.

The two receivers are enclosed within a thin aluminum mesh along with the GPS board for electromagnetic interference (EMI) protection. The layout of all internal boards is shown in Figure 4. The antennas are simple carpenter's-tape segments. They are mounted in a vertical position as shown in Figure 5.

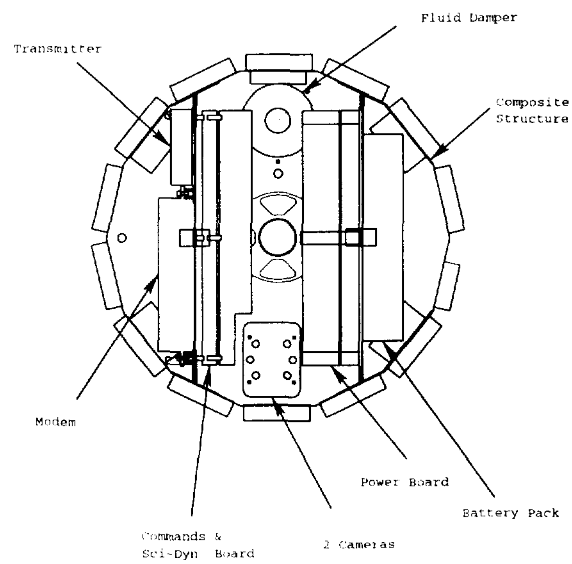

Figure 4 : Inside view

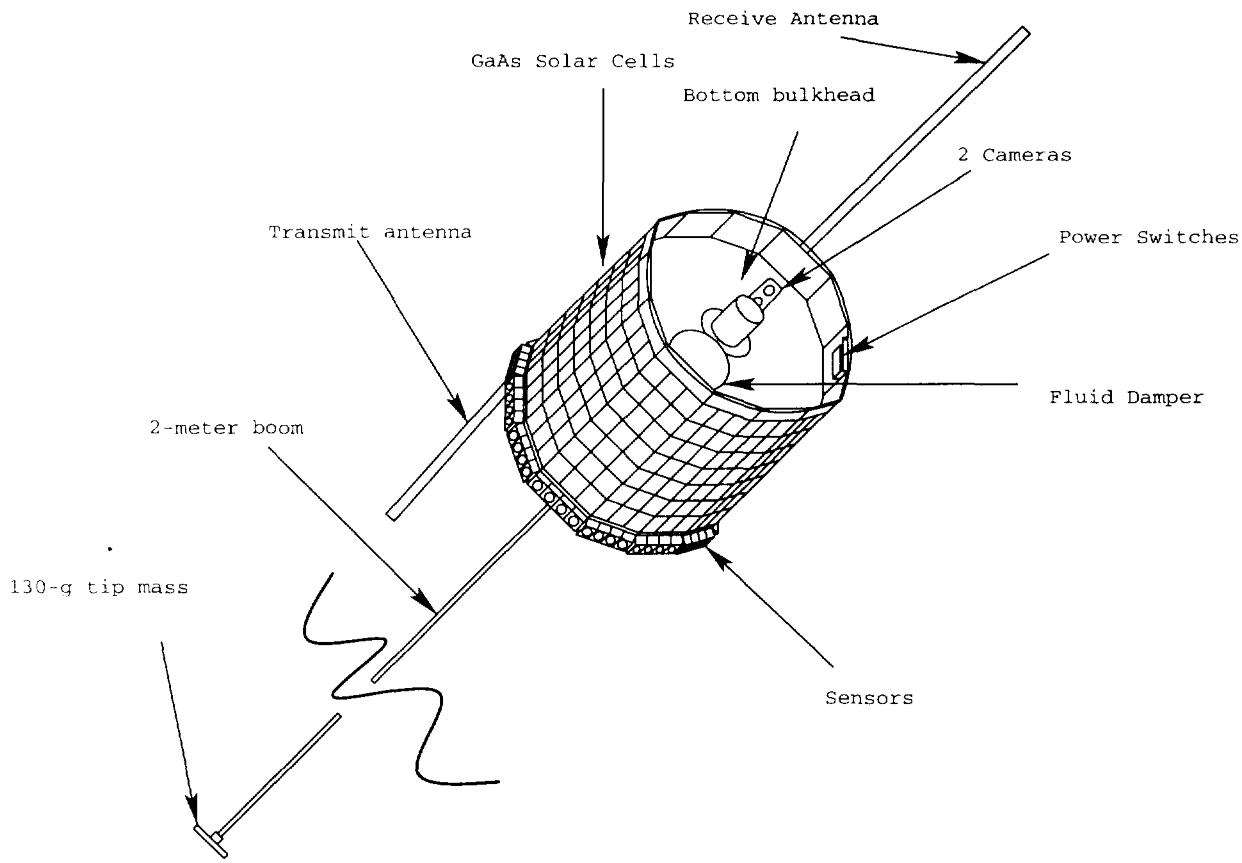

Figure 5 : Complete configuration

3.3.8 Software

The software is designed around the BekTek Spacecraft Operating System. This operating system offers a real-time multi-tasking kernel, a message-passing facility, AX.25 protocol drivers, and a set of DMA/Interrupt-based I/O drivers designed for the Intel 80C188 microprocessor.

Within this powerful operating system, there are six applications running concurrently during the mission. These applications control all on-board operations and measurements. The modules are the watchdog timer, the attitude determination, power, science, thermal, and communications software modules, and the bootloader module.

The software system is designed to receive ground commands to run the imaging and GPS systems at desired times. Other operations, such as AMSAT voice communications, are controlled automatically depending on the power available. In addition, several onboard parameters, such as the time between thermal and attitude-sensor readings, can be easily modified from the ground.

3.3.9 Thermal

Temperature transducers are mounted on the CPU, battery box, transmitter, receiver mesh, and modem to monitor operation temperatures. The transducers on the CPU, transmitter, and modem are designed into the boards. If the temperature of any system exceeds operating limits, safety

features in the software will turn the system off to prevent damage. Additional sensors are placed on the inside walls of the composite bus to monitor the thermal behavior of the composite material in the space environment.

Silverized Teflon is applied to all exposed surfaces of the structure to help reflect radiation. In addition, a black thermally conductive paint is used on the interior of the satellite to ease passive thermal control.

3.3.10 System Integration

Integration of all subsystems into the final satellite system is handled by the systems team. Cross-subsystem communication and design is also monitored to ensure optimization of weight, volume, power, functionality, and construction process. Assembly and test procedures are handled by a combination of the systems team and ground support, and EMI shielding is dealt with by all subsystems designing printed-circuit boards.

Currently ASUSat 1 is scheduled for launch in September 1997. The development structure and systems are going through the final stages of testing. Most of the components are complete and the qualification prototype is scheduled for completion in early March 1997. This system will go through full qualification testing during January, and the final vehicle is scheduled for construction immediately following qualification testing.

3.3.11 Meeting Structure

An organized meeting structure helps ensure communication between subsystems and their members. A one-hour weekly meeting is held and all members of the project attend. These meetings consist of general announcements, updates, and reports of the progress of each subsystem. Some detail is discussed, but usually separate meetings are set up afterward to discuss topics in more detail.

Each subsystem has a separate one hour meeting once a week to discuss tasks within their group and help each other out with any stumbling points.

There is one systems meeting each week for about an hour. These are mainly for subsystem leaders to get together and discuss certain topics in more detail, but others are encouraged to attend also. The program manager is the systems team leader and all other team members are considered members of the group. Topics discussed incluse budgets, weight allocations, timelines, schedules, interfacing, and other items which involve communication between subsystems.

3.3.12 Documentation

Documentation is essential because of "short term" student involvement due to graduation or the end of a semester. In general, more time is spent on documentation than in meetings.

Weekly reports are required from all members of all teams. They write one half to one page each week on what they accomplished, who they contacted, and show all calculations, drawings, and other relevant information. These reports have been saved since the project began, and hard copies are made available to all students so they can look up past research and avoid duplicating work that has already been done.

A Documentation and Drawing numbering system has been initiated for ASUSat1. The titles of documents include SAT1-DOC-0010, and the drawings SAT1-DWG-0010. Revisions are denoted by anther dash at the end with the revision number. All of the documents described in the following paragraphs are numbered in this manner.

A personnel list is constantly kept updated as students come and go. Information on this list includes student positions, telephone numbers, and e-mail addresses so they can contact each other about questions or concerns.

The contact list is kept up to date on industry and faculty contacts and telephone numbers so the students know who to talk to next time help is needed in a certain area.

A general program schedule with project phases and reviews is kept up to date along with subsystem schedules, which include more details and work planned on a weekly basis.

The Technical Design Document was used in the beginning of the project as an intro to newcomers to the project and a general overview.

The Mission Timeline and Operations Plan is a detailed account of what will occur in orbit operations. This timeline is a major design driver.

The Component List provides complete details on part, source, quantity, cost, lead time, weight, and size.

Other Information Sheets are always surfacing for information on power budgets, commands required, data sizing, temperature limits, and other information affecting several of the subsystems.

The Interface Control Diagram is a top level block diagram with connections detailed out. This diagram is enlarged and placed on the wall in the student lab for constant reference and penciling in revisions.

The System Specifications Document provides a complete, technical record of the system design. It includes subsystem descriptions, their requirements, inputs and outputs, and their environmental characteristics.

The Component Specifications Document provides a technical record of the internal workings of all components. It serves as documentation of hardware design and construction plans.

Interconnect Diagrams provide more detail on the power and data interconnects between boards, and pinouts for cabling determination. These diagrams are hung on the lab walls for revisions.

Structural Layout Drawings are used to map out every bolt hole and pass through in the structure, as well as placement of sensors and other components.

The Interface Control Document includes exact physical interfacing details with the launch vehicle, both electrical and mechanical.

A Safety Report includes descriptions of all test results, a complete material list with outgassing addressed, mechanism descriptions, proof of containment, and addresses any hazardous materials.

The Test Procedures are a detailed, step by step plan of all environmental and integration tests performed.

Assembly Procedures list the details of putting the entire satellite together during final integration.

Other subsystem documents exist for special purposes, such as new member documents and software documentation.

3.4 Conclusion

The small satellite is an important training tool for the next generation of space scientists and engineers. The ASUSat 1 project, has provided over 300 students with hands-on experience in a real space program. They have participated from the initial concept, through the design and instrumentation, and will participate on through flight, ground operations, and data collection. The result is an intricate package of low-cost, light-weight, student-designed electronics and mechanisms that function as a complete system.

This system is also an important research endeavor. A variety of innovative solutions have been developed to meet the challenge to design and construct an advanced and innovative nanosatellite within very severe constraints on mass, size, and budget. The resulting spacecraft (ASUSat 1) incorporates a variety of innovative technological features: all composite structure, student-designed low-cost attitude-determination system, terrestrial components which were space-rated by the students, low-cost cameras, and so forth.

The future of interplanetary exploration must be based on the development of lower-cost missions, and the design philosophy applied to ASUSat 1 can help provide the fundamental change required to create the next generation of interplanetary nanosatellites. Cost and launch mass are determined first and a meaningful scientific mission is chosen which fits those constraints. In the spirit of this philosophy, then, the space community should be challenged to produce a valid scientific mission with seemingly impossible mass and cost constraints. The ASUSat 1 team feels that this is the kind of challenge required to provoke the fundamental change necessary to continue the exploration of the solar system in the 21st century.

3.5 References

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APPENDIX A

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Education:
Ph.D., Engineering Mechanics, Virginia Polytechnic Institute & State University, December 1981
M.S., Engineering Mechanics, Virginia Polytechnic Institute & State University, June 1980
A.B. in Mathematics, Goucher College, May 1977

Professional Experience:

December 1994-Present	Associate Director, NASA Space Grant Program, ASU
July 1992-Present	Professor, Mechanical & Aerospace Engineering, ASU
August 1993-August 1996	Director, Aerospace Research Center (ARC), Arizona State University (ASU)
August 1985-June 1992	Associate Professor, Mechanical & Aerospace Engineering, ASU
September 1982-August 1985	Assistant Professor, Mechanical Engineering, Stanford University
June 1977-December 1981	Aerospace Technologist, NASA/Langley Research Center

Awards and Recognitions:

1997	Fellow, American Society of Mechanical Engineers, July
1997	Member of ASU Team selected as Finalist for Boeing Outstanding Educator Award
1997	Invited for Poster Session on Capitol Hill sponsored by Council on Undergraduate Research (ASUSat 1), April 10
1997	2nd in "Best Overall Design" (Moon Devil III), 4th Moon Buggy Race, US Space & Rocket Center, Huntsville
1997	Article (ASUSat 1), *PRISM* (from American Society of Engineering Education), April
1996	Cover story (ASUSat 1), *Graduating Engineer* (from Peterson's Magazine Group), Volume 18, Issue 1
1996	"Best Overall Design" and 2nd in Race (Moon Devil II), 3rd Moon Buggy Race, US Space & Rocket Center, Huntsville
1996	Distinguished Mentor of Women Award, Faculty Women's Association, ASU
1995	1st Place in Student Competition at 9th AIAA/USU Small Satellite Conference, Faculty Advisor
1995	Bronze (ASU) President's Medal for Team Excellence
1994-95	Outstanding Faculty Graduate Mentor Award from the Graduate College, ASU
1994	1st Place in Student Competition at 8th AIAA/USU Small Satellite Conference, Faculty Advisor
1993-94	Undergraduate Teaching Award from College of Engineering & Applied Sciences, ASU
1988-89	Professor of the Year, Pi Tau Sigma, ASU
1988	AIAA Excellence in Teaching Award, ASU
1991	Faculty Awards for Women in Science and Engineering, National Science Foundation
1984	Presidential Young Investigator Award, National Science Foundation
1978	Outstanding Achievement Award from NASA/Langley Research Center
1976	Outstanding Summer Employee Award from NASA/Langley Research Center

Research Interests:
Computational fluid mechanics, boundary-layer transition, and flow control; low-cost space experimentation, satellite design, and launch systems; alternative-fuel transportation; enabling technologies for micro aerial vehicles; and student-designed vehicles. Recent work includes ASUSat 1, 10-pound satellite designed, built, tested, and tracked by ASU students for low-cost Earth imagery, experimental verification of composite-material models, technology demonstration of student-designed systems, boards, and sensors, and provision of audio transponder for amateur radio operators; student design, fabrication, test, and operation of human-powered moon buggy, solar and electric cars, and micro aerial vehicles; design of low-cost launch system Intrepid; Navier-Stokes simulations of boundary-layer receptivity to freestream sound; and Parabolized-Stability-Equation simulations of 3-D hypersonic boundary layers.

Service:

Member, NASA Federal Laboratory Review Task Force, NASA Advisory Council (NAC), September 94-March 95
Member, NASA Aeronautics and Space Transportation Technology Advisory Committee (ASTTAC), 1997-Present
Member, NASA Aeronautics Advisory Committee (AAC), December 1994-1996
Member, NATO/AGARD Fluid Dynamics Panel, 1995-1998
Member, NASA Aeronautics Advisory Committee Task Force on University Strategy, 1995-1997
Member, Executive Committee of the American Physical Society/Division of Fluid Dynamics, 1996-1999
Member, Board of Directors of the Society of Engineering Science, 1993-1995
Member, U.S. National Transition Study Group, 1984-Present
Member, NSF Presidential Young Investigator Workshop on U.S. Engineering, Mathematics, and Science Education for the Year 2010 and Beyond, November 4-6, 1990
Member, National Academy of Sciences/National Research Council Aerodynamics Panel which is a part of the Committee on Aeronautical Technologies of the Aeronautics and Space Engineering Board, November 1990-March 1992
Originator, Gallery of Fluid Motions of the American Physical Society/ Division of Fluid Dynamics, since 1983
Associate Editor, Annual Review of Fluid Mechanics, 1986-Present

Publications:

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48 refereed national conference proceedings papers (7 invited)
10 books and 9 articles edited, 7 technical reports written

Memberships in Professional Societies:

Fellow, American Society of Mechanical Engineers (ASME)
Associate Fellow, American Institute of Aeronautics and Astronautics (AIAA)
Member, AMSAT (Amateur Satellite Organization)
Member, American Physical Society (APS)
Member, American Society for Engineering Education (ASEE)
Member, Association for Unmanned Vehicle Systems International (AUVSI)
Member, Electric Vehicle Technology Competitions, Ltd. (EVTC)
Member, Society of Engineering Science (SES)